

RESULTS OF USING THE GLOBAL POSITIONING SYSTEM TO MAINTAIN THE TIME AND FREQUENCY SYNCHRONIZATION IN THE JET PROPULSION LABORATORY'S DEEP SPACE NETWORK

P. A. Clements, A. Kirk, and R. Unglaub
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

The Jet Propulsion Laboratory's Deep Space Network (DSN) consists of three tracking stations located in California, Australia, and Spain, each with two hydrogen maser clocks as the time and frequency standard. Close coordination of the time and frequency of the station clocks is needed to navigate spacecraft to the outer planets. A recent example was the Voyager spacecraft's encounter with the planet Uranus in January 1986. The clocks were adjusted with the goal of minimizing the time and frequency offsets between the sites at encounter. This paper describes how the time and frequency at each complex is estimated using data acquired from Global Positioning System Timing Receivers operating on the NBS/BIH (National Bureau of Standards/Bureau International de l'Heure) tracking schedule. These data are combined with other available timing receiver data to calculate the time offset estimates. The adjustment of the clocks is described. It was determined that the long range hydrogen maser drift is quite predictable and adjustable within limits. This enables one to minimize time and frequency differences between the three sites for many months by matching the drift rates of the three standards. The paper will describe the data acquisition and processing techniques using a Kalman filter to make estimates of time and frequency offsets between the clocks at the sites and UTC(NBS) [Coordinated Universal Time realized at NBS].

INTRODUCTION

The DSN is a collection of three sites of antennas used to track spacecraft. These sites are located at Goldstone, California; Tidbinbilla, Australia; and Robledo, Spain. Each site contains a frequency and timing system which provides the required frequencies and timing pulses for all of the subsystems in that site. There are two hydrogen masers located at each site: the first acts as the master clock and provides the primary frequency source, and the second acts as a backup. The backup hydrogen maser is kept syntonized to the primary, particularly during critical missions, so that a switch from primary to secondary would have a minimum effect on DSN users.

A requirement exists that timing pulses and frequencies distributed throughout the site be coherent. This requirement precludes the use of microsteppers to keep the site's clocks synchronized to some uniform timescale. Therefore, the master clock exhibits the characteristic hydrogen maser drift in frequency.

The process of tracking spacecraft involves all three sites working in

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concert to continuously track spacecraft as the earth turns. At Voyager's Uranus encounter the round trip signal transmission time was very long (about five hours). A signal, sent from one site to the spacecraft, then transponded and sent back to earth, is received by a second site. The Neptune encounter, which is to occur in 1989, will require the transponded signal to be received by the second and third site. This procedure requires accurate synchronization and syntonization between sites to measure round trip signal transmission time and signal doppler shifts when communicating with the spacecraft. Other requirements such as Very Long Baseline Interferometry (VLBI) and radio science also require accurate synchronization and syntonization among the DSN clocks.

Presently, the DSN Frequency and Timing system (DFT) requirements are to maintain synchronization between sites to within ± 20 microseconds with a knowledge of ± 10 microseconds. Inter-site syntonization is to be maintained to within 1×10^{-12} df/f with knowledge of $\pm 3 \times 10^{-13}$ df/f. It is possible that navigation requirements at the Voyager Neptune encounter will be knowledge of frequency to less than 1×10^{-13} df/f.

It needs to be emphasized that the DSN is a user of timescales and not a producer. We need to adjust our clocks from time to time to keep them syntonized and synchronized with each other. It is convenient for us to use the UTC(NBS) time scale as a reference. First, it is a uniform and continuous time scale. Second, the proximity of the NBS Time and Frequency division to JPL (approx. 1000 Km) has historically made NBS the most accessible time scale to the California DSN site due to the short airplane flight to carry a clock. The use of the Global Positioning System (GPS) time transfer method has made the UTC(NBS) accessible to all DSN sites, so we have created an ensemble of clocks using UTC(NBS) as the reference. JPL has a contract with NBS which provides the JPL with access to UTC(NBS) and also to the cesium clock associated with WWVH (the NBS time broadcast radio station) in Hawaii, using the data from their GPS timing receiver.

THE GPS TIME AND FREQUENCY COORDINATION SYSTEM

JPL has installed GPS timing receivers at the three DSN sites (Ref 1). These receivers get a timing pulse from the master clock at each DSN site which is the "on line" hydrogen maser. The data from these receivers and other data are combined using a Kalman filter to produce estimates of time and frequency offsets of the DSN sites with respect to UTC(NBS). JPL uses the tracking schedule published by NBS/BIH. This schedule allows mutual views with receivers whose tracking data are posted on the GE MK III RC28 Catalog, which is administrated in the United States by the United States Naval Observatory¹. Figure (1) is a schematic diagram showing the clocks used and the possible mutual views which are available.

The data are gathered by telephone once per week from the receivers in the DSN from the data base at NBS and from the GE MKIII database using an IBM XT personal computer. This is certainly a change from just a few years ago when we depended on travelling clocks and LORAN. Now we are able to observe

¹ For further information, contact Catalog Administrator, F.N. Withington,

USNO Time Service Division, Washington, D.C. 20390, USA

the clocks, control them, and provide a guaranteed high accuracy synchronization and syntonization for the users of the DSN.

OPERATION OF THE CLOCKS

During the initial installation of a hydrogen maser frequency standard at a DSN site, a calibration sequence is performed that includes the following steps:

- A. Verify environmental stability with unit in final position.
- B. Set final operating parameters.
- C. Degauss magnetic shields.
- D. Set internal bias field to required value.
- E. Spin-exchange tune the hydrogen maser cavity.
- F. Calibrate hydrogen maser rate to NBS (synthesizer calibration)
- G. Calibrate rate of back-up standards.
- H. Set master and back-up clocks.

Figure 2 is a quadratic least square fit to the time offsets of the DSN site's clocks with respect to UTC(NBS), and Figure 3 is a least square linear fit of the frequency of the clocks with respect to UTC(NBS). The maser frequency drift of approximately 4.5×10^{-15} df/f per day is well behaved and could be matched even closer between the three hydrogen maser clocks. Knowledge of this drift allows us to maximize the time interval between rate adjustments. After the masers are calibrated the cavity is deliberately mistuned so that the average frequency offset with respect to NBS is near zero between rate changes. Average time difference between the three site's clocks and NBS is minimized by choosing the appropriate initial time offset. By spin-exchange tuning the hydrogen maser after one to two years and recalibrating the synthesizer, we will be able to determine the long term drift that is due to mechanisms other than the cavity.

The back-up standards are monitored on-site with respect to the prime standard so that traceability to NBS is maintained. The rate of these units is manually corrected when necessary so that upon switching from prime to back-up standard, the frequency shift is minimal. Figure 3 shows that this was not accomplished very well. From about day-of-year (DOY) 100 on, back-up standards were shifted in and out for various reasons in Spain and Australia. The GPS system gives near real time visibility of clock performance at the three sites and enables operational control personnel to evaluate and improve overall system performance.

EXAMPLE OF THE VOYAGER ENCOUNTER

As the Voyager spacecraft approaches the planet, calculations are made to correct the estimates of the spacecraft's location. The accurate measurements required for these calculations cannot be made until about 10 to 20 days before encounter. With these measurements, adjustments can be made to produce the desired trajectory by the planet. By having the DSN site's clocks synchronized and syntonized through the encounter period,

accurate measurements of the spacecraft's location can be made.

To satisfy encounter requirements we decided to adjust the rate and offsets at each DSN site so that at encounter the frequency and time difference between each station and NBS would be near zero. This was done about two months prior to encounter.

Daily GPS common view time observations were made to monitor the clock performance at each station. Fig. 4 shows the time offsets with respect to NBS. Worst case station-to-station and station-to-NBS offset was less than 500 nanoseconds during the encounter period. Note the several prominent time steps at Australia on days 355, 20, 77, and 87. The master clock at each site is driven by a 5 MHz "Flywheel" oscillator which is phase locked to the primary standard 5 MHz output. The phases of the back-up standards are not maintained at zero with respect to the prime so that upon switching to the backup standard, a time change of up to \pm 100 nanoseconds may result. This happened on the above mentioned days in Australia when for various tests and experiments, frequency standards were shifted. On about day 100, Spain was directed to shift to a back-up standard without first matching the frequency. A frequency change of about 6×10^{-13} df/f led to the rapid divergence of time from DOY 100 on.

TIME AND FREQUENCY OFFSETS USING THE KALMAN FILTER

The difference of the data from the receiver pairs is taken to produce mutual view values for clock pair offsets, one value each day for each spacecraft that is used for a mutual view for a given receiver pair. Using space vehicle i,

$$(c_b - c_a + n_{svi})_i = (gps - c_a + n)_i - (gps - c_b + n)_i$$

where n is the noise, n_{svi} is the total common view noise, c_a c_b are the ground clocks, and gps is the space vehicle clock.

A mean C_{ba} of the set of mutual view differences is then calculated along with the mean time T.

$$C_{ba} = \frac{1}{m} \sum (c_b - c_a + n_{svi})_i,$$
$$T = \frac{1}{m} \sum t_i$$

where m is the number of daily observations, and t_i is the time of the observation using space vehicle i.

These mean values are used as inputs to the Kalman filter, which has the effect of giving each space vehicle's common view measurement equal weight. This tends to ignore the bias problem which was described by M. A. Weiss (Ref. 2). Also, if a measurement is not made for some spacecraft on a particular day, then the biases of the individual spacecraft measurement tends to offset the estimate for that day, an undesirable side effect.

The Kalman filter is a classical design, written in BASIC and run on an IBM

PC-AT. The output of the filter is the time, frequency and frequency drift of each clock with respect to UTC(NBS). An estimate of the time, frequency, and frequency drift for any point between endpoints of the data set can be made by smoothing to that point. The procedure is to smooth to 00 hours UTC each day and use that value of the state vector as the estimate of the time and frequency offset of the clock with respect to UTC(NBS). The data are handled in 30 day batches, with each new batch started off with the state vector and the co-variance matrix from the previous batch.

Figure 4 shows the detail of the time offset of each of the clocks through the encounter to about DOY 130. The data were generated by the Kalman filter, and each day is a point smoothed to 0 hours UTC. Each of the clocks is referenced to UTC(NBS). However, because the estimate is for the same time, the relation between the clocks at any two sites can be obtained by subtracting the value of one site from that of the second.

Figures 5, 6, and 7 show the estimated value of frequency of the site's clocks before, during, and after encounter. On top of these smoothed values are estimates of frequency obtained from the mutual view data by making a linear least squares estimate of the data over about ten day groups of data. These estimates were done manually with judicious choice of data.

Notice the boxed-in detail on Figure 5, the frequency offset between California and UTC(NBS). This indicates that there was almost 1×10^{-13} df/f change in frequency over a period of 10 to 15 days. Unexplained frequency changes of this magnitude have been noticed in hydrogen masers during tests at JPL. However, the mysterious thing is that the other clocks, Australia and Spain, showed similar frequency changes at the same time. The Kalman smoother output agrees with the hand calculations of frequency using the mutual view data which indicates the filter is not causing the appearance of similar frequency changes in the several clocks.

One would conclude that the NBS timescale wiggled. Indeed, the wiggle seems to have been at NBS, but not the timescale. At that time JPL was not accessing the data from the timescale, but from clock 9 at NBS. A check with NBS confirmed that clock 9 experienced a similar frequency excursion at that time. Two conclusions can be drawn from this: the Kalman smoother produces good estimates of the clock performance and the need to make sure the data is from the UTC(NBS) timescale. This procedure was changed late in 1986; JPL presently accesses the UTC(NBS) timescale.

Figure 8 shows the values of Allan variance of frequency estimates of the three site's clocks produced by the Kalman smoother. Nominal expected drift of the hydrogen masers which are deployed is 4.5×10^{-15} df/f per day slope. The California line follows the expected performance of the field hydrogen masers fairly well. At four days or less, the Spanish and Australian Allan variance has considerably worse than expected performance. The Spanish Allan variance settled down to hydrogen maser performance at about eight days. The Australian estimates never seem to settle down.

CONCLUSIONS

Daily estimates of frequency with errors of less than 1×10^{-13} df/f are available on a routine basis. It appears that this can be reduced to several parts in 10^{-14} df/f in the next few months. We have shown that we can operate the DSN continuously with clocks which are syntonized to within 3×10^{-13} df/f and synchronized to within a microsecond. By matching the drift rates of the clocks it might be possible to routinely match the synchronization and syntonization even more closely.

This year's experience has shown that we need to develop better methods to assure the secondary hydrogen maser is kept closely syntonized with the primary maser.

ACKNOWLEDGEMENT

A special thanks to Dr. James A. Barnes of Austron, Inc. for his instruction in the construction and operation of Kalman filters.

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2. M. A. Weiss, Proc. 17th Ann. Precise Time And Time Interval Applications and Planning Meeting, pp. 261-273

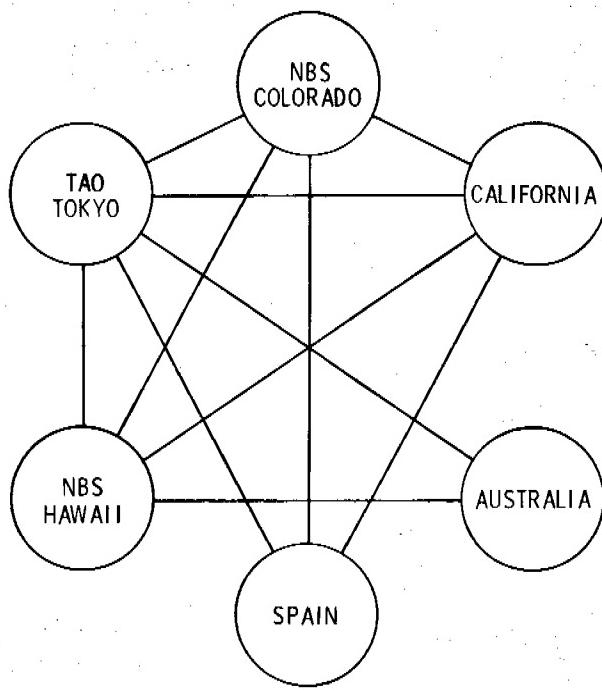
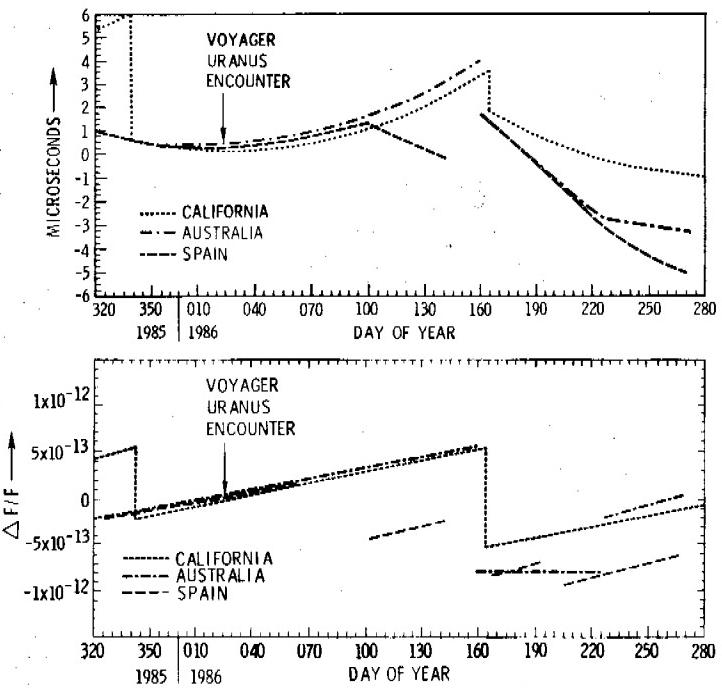


Figure 1. Possible GPS Mutual Views available to Measure the DSN Clocks.



Figures 2 and 3. Time and Frequency Offset with Respect to UTC (NBS).

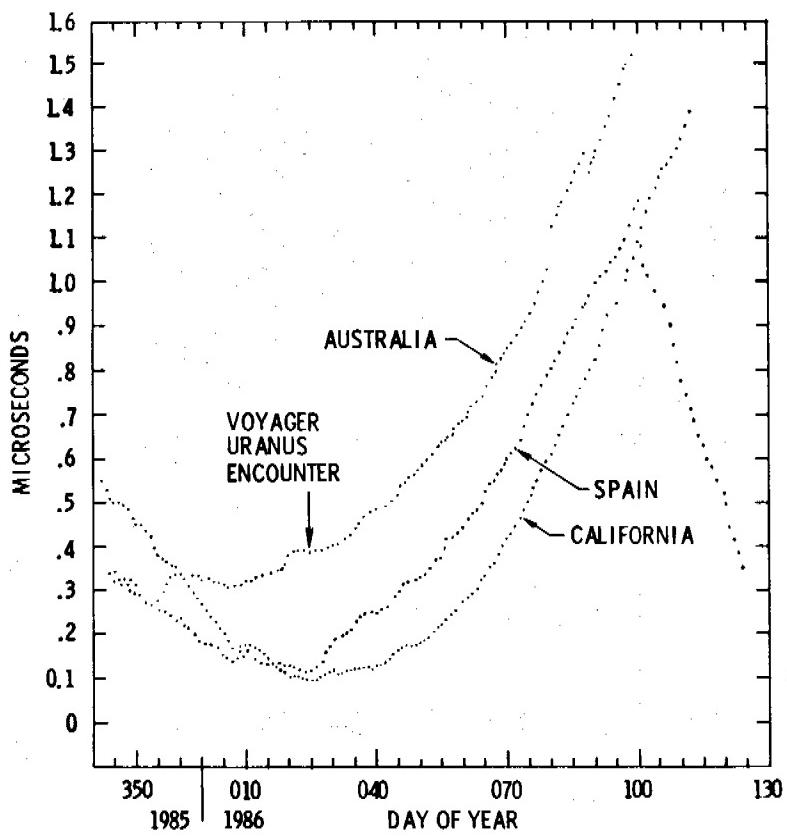


Figure 4. Time Offset with Respect to UTC (NBS)
(Output of Kalman Smoother).

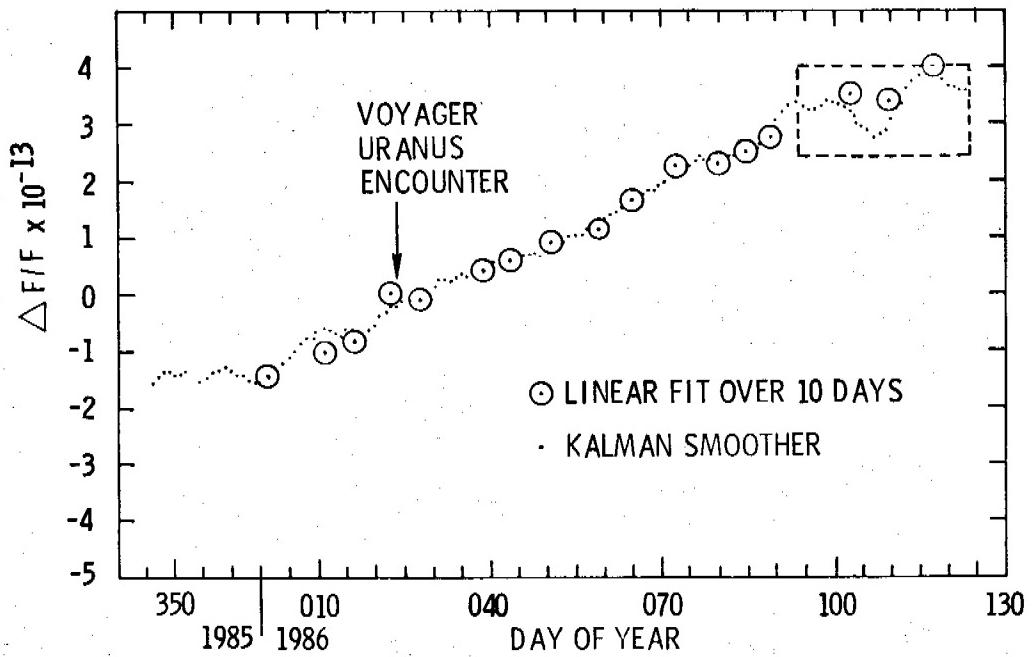


Figure 5. Frequency Offset - California-UTC (NBS)

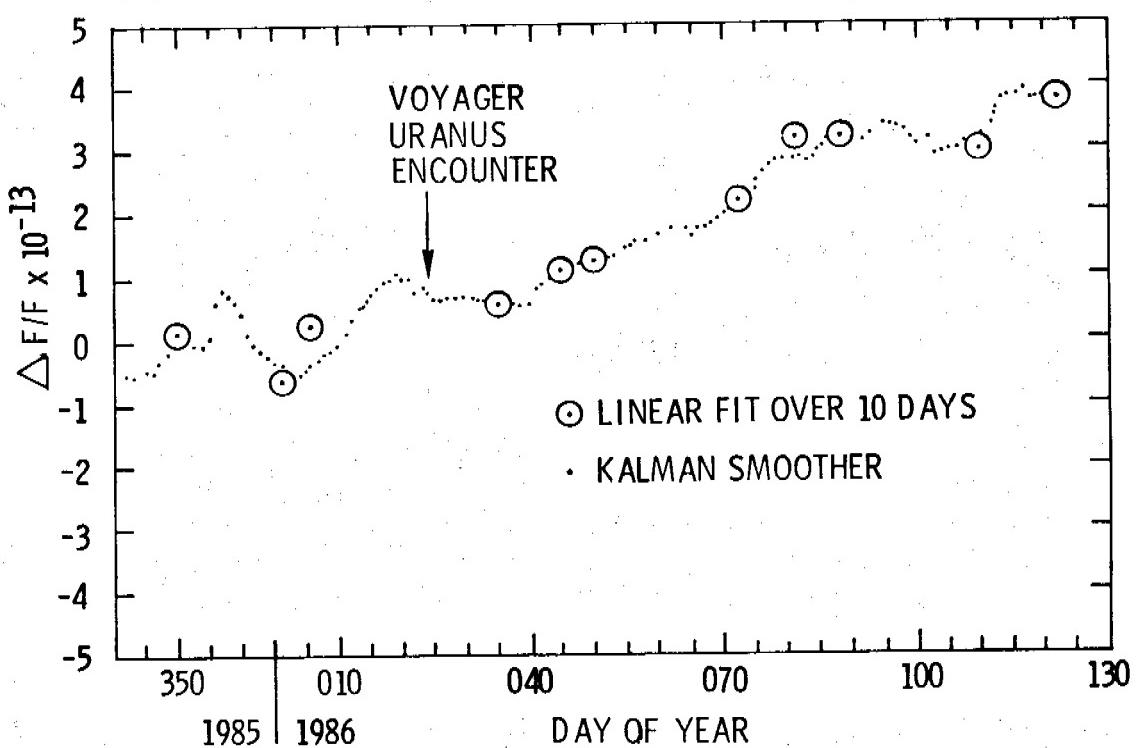


Figure 6. Frequency Offset - Australia-UTC (NBS)

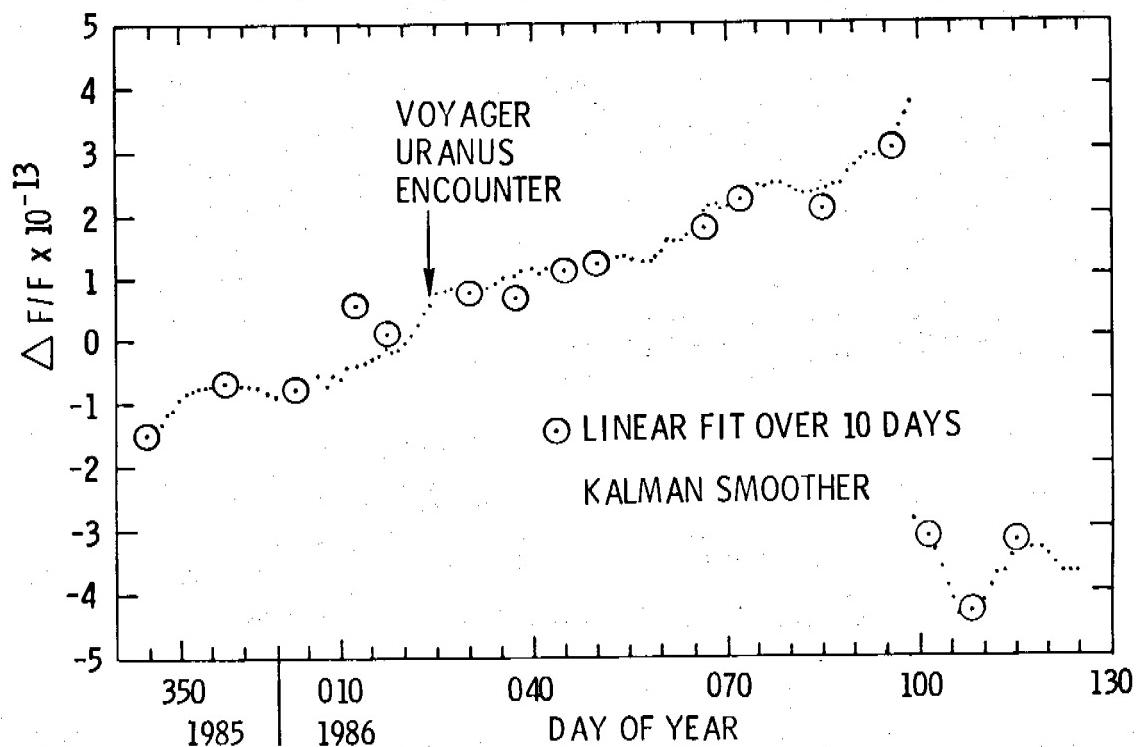


Figure 7. Frequency Offset - Spain-UTC (NBS)

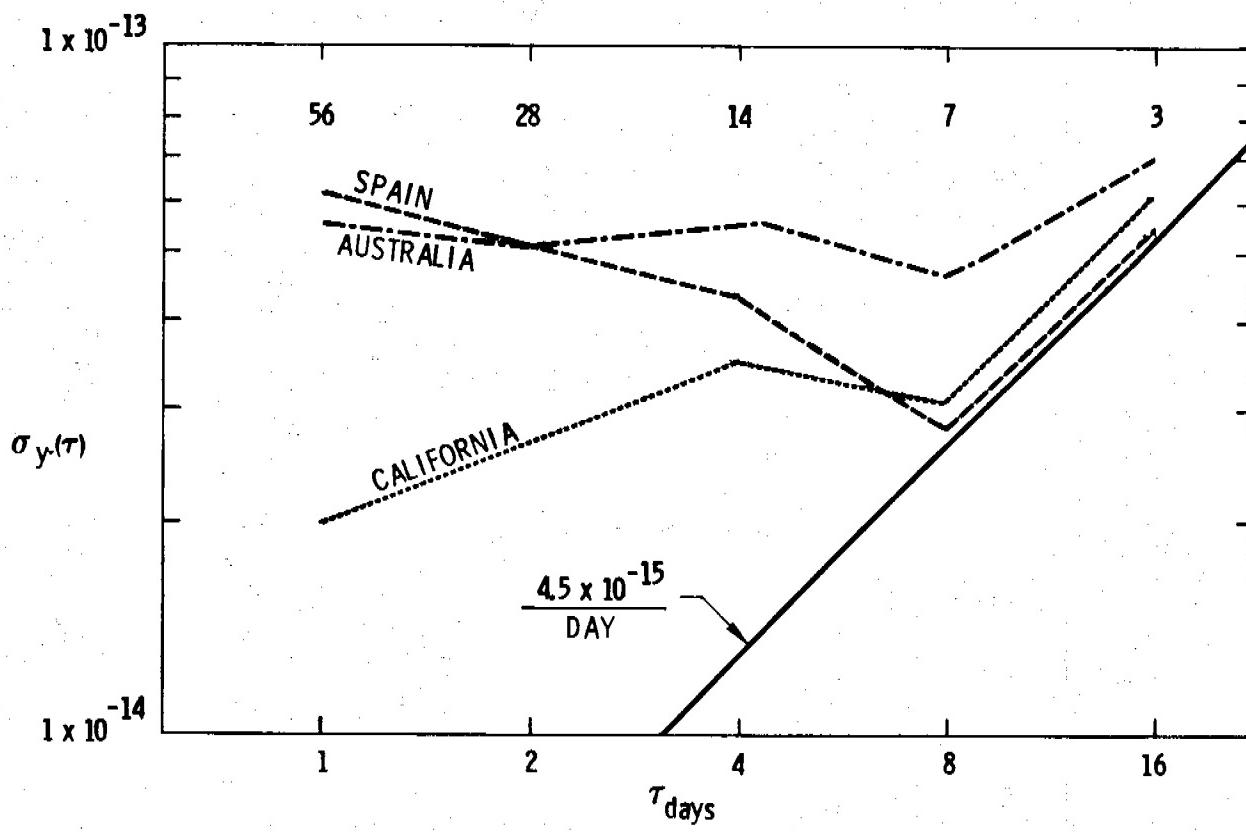


Figure 8. Allan Variance with Respect to UTC (NBS)

QUESTIONS AND ANSWERS

SAM WARD, JET PROPULSION LABORATORY: We know that the process of bringing the oscillators in phase is a part of a procedure that the operators failed to follow when they switched standards. We have a phase calibrator that feeds references up to the antenna. If the two standards are more than 50 ns apart when they are switched, the phase calibrator drops lock. Procedurally, anytime there is a planned or unplanned switch of the frequency standards, the phase should be adjusted.

The perturbation in Spain was, once again, an operational thing. It happened in the middle of the night. At two AM, the power system that fed the satellite station, the Apollo station. It developed a ground fault and the electrician on duty unloaded one line at a time to try to isolate the fault. In the process, he turned off our UPS, the Uninterruptable Power System. This caused the clocks to stop and the operators were not familiar with the procedure for resetting them. As a result, the clocks were set with a huge error.

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS: The sigma tau deviation having a hump at three and a half days suggests something with a weekly basis. One would ask the question as to what has a cycle of once per week.

MR. KIRK: According to Sam's theory, the weekends are different from the rest of the week. We don't know what goes on. Now, with this visibility by using the GPS system which is much more nearly real time than previous methods, I think that we can get a handle on what they do over there, or even at Goldstone, and what can we do about it? Assuming that it is an operator problem that introduces a weekly perturbation.

MR. ALLAN: As a second comment, we at NBS watch not only JPL but several other national laboratories. We will go back and look very carefully at the data from day 100 onward. To our knowledge there were no deviations of that size during that period.